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(54) Process for manufacturing high-sensitivity accelerometric and gyroscopic integrated sensors, and sensor thus produced

(57) To increase the sensitivity of the sensor, the movable mass (40) forming the seismic mass is formed starting from the epitaxial layer (13) and is covered by a weighting region of tungsten (26c) which has high density. To manufacture it, buried conductive regions (2) are formed in the substrate (1), then, at the same time, a sacrificial region is formed in the zone where the movable mass is to be formed and oxide insulating regions (9a-9d) are formed on the buried conductive regions (2) so as to cover them partially; the epitaxial layer (13) is then grown, using a nucleus region; a tungsten layer (26) is deposited and defined and, using a silicon carbide layer (31) as mask, the suspended structure (40) is defined; finally the sacrificial region is removed, forming an air gap (38).

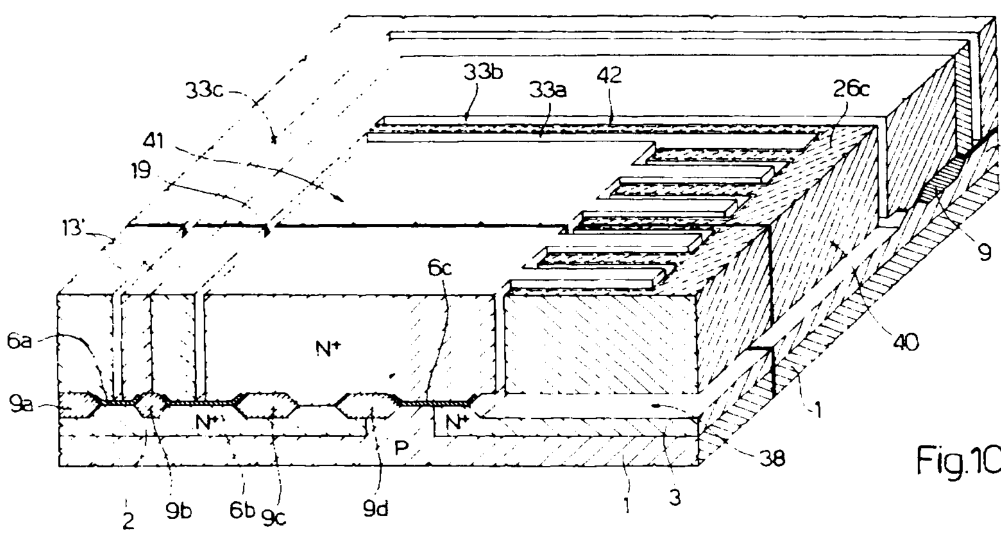

Fig.10

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Description

[0001] The invention relates to a process for manufacturing high-sensitivity accelerometric and gyroscopic integrated sensors and a sensor thus produced.

[0002] As is known, the use of electro-mechanical microstructures of semiconductor material, the manufacture of which utilizes microelectronics techniques, has recently been proposed for producing accelerometers and gyroscopes. These silicon micromachining techniques make it possible to produce different types of angular velocity and acceleration sensors. In particular, at the present time prototypes operating according to the piezoelectric, piezoresistive, capacitive, threshold, resonant and tunnel effect principle have been proposed.

[0003] Reference will be made below to an accelerometric sensor of differential capacitive type, i.e. one in which acceleration induces the movement of a seismic mass which constitutes the electrode common to two capacitors, electrically connected, by varying the two capacitances in opposite directions (differential variation of capacitance).

[0004] Historically, integrated micro-structures have been manufactured by preferably using the "bulk micromachining" technique in which a wafer of single-crystal silicon is machined on both faces. This technique is, however, incompatible with the process steps for producing components of the circuit which processes the signal picked up by the sensitive element, as required at present.

[0005] It has therefore been proposed to use the technique of "surface micromachining" in which the sensitive element is made of multi-crystal silicon and suspended structures are formed by depositing and successively removing sacrificial layers. This technique is compatible with the current integrated circuit manufacturing processes and is therefore preferred at present. The integrated micro-structures produced with this technique are, however, relatively insensitive to acceleration and angular velocity. In fact, having a mass of the order of a few tenths of a microgram, they suffer the effects of thermodynamic noise caused by the Brownian movement of the particles of the fluid in which they are immersed (see, for example, the article by T.B. Gabrielson entitled "Mechanical-Thermal Noise in Micromachined Acoustic and Vibration Sensors", IEEE Transactions on Electron Devices, vol. 40, No. 5, May 1993). The upper limit to the mass obtainable with these structures is imposed by genuinely technological reasons; the deposition of very thick films does, in fact, involve extremely long wafer machining times and renders the surface of the wafer unsuitable for the successive operations such as the lapping of the wafers.

[0006] A technique for machining the epitaxial layer ("epitaxial micromachining") is also known, which enables micro-structures to be obtained with inertial masses which are higher and hence more sensitive, but not yet at a sufficient value for practical applications.

[0007] The object of the invention is to improve a process for manufacturing an accelerometric and gyroscopic sensor according to the technique of "epitaxial micromachining" so as to increase its sensitivity further.

[0008] The invention provides a process for manufacturing a high-sensitivity accelerometric and gyroscopic integrated sensor and a sensor thus produced, as defined in Claims 1 and 10 respectively.

[0009] For an understanding of the invention a number of preferred embodiments will now be described, purely by way of non-exhaustive example, with reference to the accompanying drawings in which:

- Figs. 1-8 show transverse sections at different points through a wafer of semiconductor material during successive steps of the manufacturing process according to the invention;
- Fig. 9 shows a transverse section taken in a plane perpendicular to Fig. 8;
- Fig. 10 shows a perspective view of the sensor obtained with the process of Figs. 1-9;
- Fig. 11 shows a top view of the sensor of Fig. 10; and
- Figs. 12 and 13 show transverse sections of a portion of a wafer in two successive manufacturing steps according to a different embodiment of the process.

[0010] An embodiment of a capacitive-type accelerometric or gyroscopic sensor according to a first embodiment of the process will now be described with reference to Figs. 1-10, in which the thicknesses of the various layers of material are not to scale and some layers are not shown in all the illustrations for reasons of representation.

[0011] According to Fig. 1, buried N^+-type conductive regions 2, 3 to form buried interconnections are formed in a substrate 1 of single-crystal silicon of P-type conductivity, using conventional masking and implantation techniques. A pad oxide layer 5 is formed, e.g. grown thermally, on the surface 4 of the substrate 1, and a silicon nitride layer 6 is deposited on it; the silicon nitride layer 6 is then defined and removed selectively in the sensor zone 7. Then the portions of the surface of the substrate 1 not covered by the layer 6 are locally oxidated, forming oxide regions comprising a sacrificial region 8 (surrounded at the sides and underneath by the buried conductive region 3) and buried oxide regions 9a, 9b, 9c and 9d at the buried conductive region 2, obtaining the structure of Fig. 2.

[0012] Through suitable masking steps, portions of the layers 5, 6 are then removed in the sensor zone 7 where the buried contacts of the sensor and of the silicon nitride layer 6 are to be formed in the circuitry and interconnection area 10, obtaining the structure of Fig. 3, in which the pad oxide layer 5 underneath the silicon nitride layer 6 is not shown and 6a, 6b and 6c denote the

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portions of nitride included, respectively, between the buried oxide regions 9a and 9b; 9b and 9c and the regions 9d and 8.

[0013] An amorphous or multi-crystal silicon layer 12 is then deposited, as shown in Fig. 4. By means of a phototechnique and plasma etching step, the amorphous or multi-crystal silicon layer 12 is removed, apart from the sensor zone 7, forming a silicon region 12' representing the nucleus for a successive epitaxial growth step. By means of chemical etching, the pad oxide layer 5 is then removed where exposed and epitaxial growth takes place with formation of a pseudo-epitaxial, so to speak, P-type layer 13 which, in the sensor zone 7, has a multi-crystal structure (multi-crystal region 13') and a single-crystal structure elsewhere (single-crystal region 13"). A wafer 14 as shown in Fig. 5 is thus obtained.

[0014] The pseudo-epitaxial layer 13 is then doped with doping ions suitable for determining an N-type conductivity to form deep regions: in particular, as shown in Fig. 6, in which a portion of the wafer 14 is shown slightly displaced to the left with respect to Figs. 1-5, a deep N^+-type region 18 is formed in the single-crystal region 13" and extends from the surface 16 as far as the buried conductive region 2, to connect electrically this buried conductive region 2 to the surface 16, and an N^+-type well 19 which extends from the surface 16 as far as the buried conductive region 3 (see Fig. 7) and, partially, the buried conductive region 2, is formed in the multi-crystal region 13'. In particular, the well 19 extends above the buried oxide regions 9c, 9d and half of the buried oxide region 9b, electrically contacting the buried conductive region 2 in the area included between the buried oxide regions 9c, 9d not covered by the portions of nitride 6a-6c.

[0015] The electronic components of the circuitry are then formed by means of standard steps; in the example shown, an N-type collector well 15 is formed, extending from the surface 16 of the pseudo-epitaxial layer 13 as far as the substrate 1; an NPN transistor 23 having an N^+-type collector contact region 20, a P-type base region 21 and an N^+-type emitter region 22 is formed in the collector well 15.

[0016] A dielectric layer 24 for opening the contacts, e.g. BPSG (boron phosphorus silicon glass) is then deposited on the surface 16 of the wafer 14. Then, by a suitable masking and selective removal step, the contacts are opened in the circuitry area and on the deep region 18, and a part of the dielectric layer 24 is removed from the sensor zone 7. An adhesive layer 25 (of titanium nitride for example) is then deposited, to facilitate the adhesion of the next layer to the silicon of the wafer 14, and then, by CVD (Chemical Vapour Deposition), a tungsten layer 26 (1 μm thick, for example), obtaining the intermediate structure of Fig. 6, in which the nucleus silicon region 12' has been omitted.

[0017] The tungsten layer 26 is then shaped, by means of known photo-lithographic steps, so as to form contacts 26a of the circuitry and 26b of the sensor and a weighting region 26c over the well 19, as shown in Fig. 7 in which the adhesive layer 25 is not shown. In particular, the weighting region 26c is shaped as partially shown in Fig. 10, that is correspondingly to the shape of the movable electrode of the sensor, as explained in greater detail below. A dielectric passivation layer 30 is then deposited and this is removed in the zone of the contact pads (to permit the electrical contacting of the device, in a manner not shown), and in the sensor zone 7, thus obtaining the structure of Fig. 7.

[0018] A silicon carbide layer 31, intended to form a mask for the subsequent step of excavation of the pseudo-epitaxial layer 13 and precisely of the multi-crystal region 13', is then deposited and defined; excavations are carried out for releasing the movable mass of the accelerometer, for separating the fixed and movable electrodes and for insulating the regions at different potential. Thus there are formed a trench 33a which separates the fixed part from the movable part and the fixed mass from the surrounding portion of the well 19; a trench 33b (see Figs. 10 and 11) separating the anchorage regions from the surrounding portion of the well 19; and a trench 33c separating the sensor from the rest of the chip. The structure is thus obtained which is shown in the transverse section of Fig. 8, taken on the same section as Figs. 1-7 but centred on the sensor zone 7, and in the transverse section of Fig. 9, taken perpendicular to that of Fig. 8 and showing transverse walls 34 and 35 defining the movable electrodes and the fixed electrodes of the sensor, as explained in greater detail below with reference to Figs. 10 and 11.

[0019] Finally, the sacrificial region 8 is removed by etching in hydrofluoric acid, and the zone previously occupied by this region 8 forms an air gap 38 which at the bottom separates the movable mass from the rest of the wafer; the movable mass is then etched and supported by the chip only at the anchorage zones. With a subsequent etching in plasma, the silicon carbide layer 31 is removed from all the wafer. The final structure is thus obtained which is shown in Figs. 10 and 11 in which the movable mass is denoted by 40 and the fixed mass by 41; the anchorage zones of the movable mass by 42. In particular, Fig. 11 shows the outer edge of the buried conductive region 3 in broken lines and the outer edge of the well 19 in dot-and-dash lines. Broken lines also denote the buried conductive regions 2 for forming the buried connections of the fixed mass, and 2', 2" those of the movable mass, formed at the same time and in the same way as the buried conductive region 2. Fig. 10 also shows the profile of the weighting region 26c.

[0020] As will be noted, the movable mass 40 is H-shaped; the transverse walls 34 defining the movable electrodes of the capacitive sensor, interleaved in comb-like manner with the transverse walls 35, defining the fixed electrodes, depart from its central element. The structure is therefore equivalent to a capacitor formed by two capacitors in series, each formed by a

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plurality of elementary capacitors connected in parallel.

[0021] In per se known manner, through the deep regions 18 and the buried conductive regions 2, 2', 2", 3 the movable electrodes 34 and the fixed electrodes 35 are polarized at different voltages so that when the movable mass 40 is subjected to acceleration the consequent change of distance between the movable electrodes and the fixed ones may be detected as a variation of capacitance.

[0022] The manufacture of a movable mass 40 of semiconductor material with a tungsten weighting region 26c, as described, gives the sensor high sensitivity. In fact, tungsten has high density (19.3 g/cm^3) with respect to multi-crystal or amorphous silicon (2.33 g/cm^3). Consequently, a tungsten layer 1 μm thick is virtually equivalent, from the point of view of the mechanical properties, to a 10 μm polysilicon layer. On the other hand, the deposition by CVD of a tungsten layer of the indicated thickness can easily be achieved with the conventional integrated microelectronics machining techniques.

[0023] The sensor obtained in this way thus has high sensitivity, yet benefits from the advantages typical of epitaxial machining technology and permits the integration of the sensor together with the integrated signal processing circuit.

[0024] The manufacturing process is simple to implement, using steps typical of microelectronics, and forming the metallic circuit interconnection regions and the weighting regions of the movable structure at the same time. The process is also readily controllable and repeatable.

[0025] According to a different embodiment of the invention, the buried oxide regions 8, 9 are grown in recesses previously formed in the substrate 1, after the buried conductive regions 2, 3 have been formed. In detail, according to Fig. 12, starting from the structure of Fig. 1 the oxide 5 and nitride 6 layers are formed and these are defined in a similar manner to that described with reference to Fig. 2. The portions of substrate 1 not covered by the layers 5, 6 are then etched, forming recesses 50 (Fig. 12); the recesses 50 are then filled with thermally grown oxide regions, only the sacrificial region 8' and the buried oxide region 9d' of which are shown in Fig. 13. The further steps described above then follow, starting from the removal of portions of nitride 6 and of oxide 5 where the contacts are to be formed and in the zone of the circuitry, as described from Fig. 3 onwards.

[0026] According to a further embodiment which is not shown, the sacrificial and buried oxide regions may be obtained by depositing and shaping an oxide layer.

[0027] Finally it will be clear that numerous modifications and variants may be introduced to the process and sensor described and illustrated herein, all coming within the scope of the inventive concept as defined in the accompanying claims. In particular, the components of the circuitry integrated with the sensor may be either bipolar or MOS; the conductivity of the conductive regions may be the opposite of that shown and the protective and/or adhesive materials may be replaced by others which, are equivalent as regards the functions desired.

Claims

1. A process for manufacturing an accelerometric and gyroscopic integrated sensor, comprising the step of:

   - forming a sacrificial region (8) on a substrate (1) of semiconductor material;
   - growing an epitaxial layer (13) on said substrate and said sacrificial region; and
   - removing selective portions of said epitaxial layer (13) and said sacrificial region (8) to form a movable mass (40) surrounded at the sides and separated from fixed regions (41) by means of trenches (33a, 33b, 33c) and separated from said substrate (1) by means of an air gap (38); characterized in that a weighting region (26c) comprising tungsten is formed at said movable mass (40).

2. A process according to Claim 1, characterized in that said step of forming a weighting region (26c) comprises the step of depositing and defining a tungsten layer (26) over said epitaxial layer (13).

3. A process according to Claim 2, characterized in that said step of depositing and defining a tungsten layer (26) is carried out before said step of removing selective portions of said epitaxial layer (13).

4. A process according to Claim 3, characterized in that after said step of defining said tungsten layer (26), the step of masking the epitaxial layer (13) and said weighting regions (26c) through a protective layer (31) resistant to etching of said sacrificial region (8) is carried out.

5. A process according to Claim 4, characterized in that said sacrificial region (8) is of silicon oxide and said protective layer (31) comprises silicon carbide.

6. A process according to one of Claims 2-5, comprising, before said step of depositing said tungsten layer (26), the steps of:

   - forming electronic components (23) in said epitaxial layer (13);
   - depositing a dielectric layer (24) over said electronic components;
   - forming contact openings in said dielectric layer (24); and in that said step of defining said tungsten layer (26) further comprises the step

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of forming tungsten contact electrodes (26a, 26b) for said electronic components (23) and for said accelerometric and gyroscopic sensor

7. A process according to one of Claims 2-6, characterized in that, before said step of depositing a tungsten layer (26), the step of depositing an adhesive titanium nitride layer (25) is carried out.

8. A process according to one of Claims 1-7, characterized in that the step of forming a nucleus region (12') of non-single-crystal semiconductor material on said sacrificial region (8) is carried out before said step of growing an epitaxial layer (13) and in that said step of growing an epitaxial layer (13) comprises the step of growing a multi-crystal region (13') on said nucleus region and growing a single-crystal region (13") on said substrate (1); in that said suspended mass (40) is formed in said multi-crystal region (13') and in that it comprises the step of forming electronic components (23) in said single-crystal region (13").

9. A process according to Claim 8, characterized in that said substrate (1) has a first conductivity type; in that, before said step of forming a sacrificial region (8), the step of forming buried conductive regions (2, 3) of a second conductivity type in said substrate is carried out; in that, at the same time as said step of forming a sacrificial layer (8), electrically insulating material regions (9a, 9b, 9c, 9d) are formed, extending on said buried conductive regions (2) and delimiting therebetween portions of selective contact of said buried conductive regions; in that, after said step of growing an epitaxial layer (13), the step of forming deep contact regions (18) extending from a surface (16) of said epitaxial layer as far as said buried conductive regions to form deep contacts is carried out.

10. An accelerometric or gyroscopic integrated sensor, comprising a substrate (1) and an epitaxial layer (13) of semiconductor material, said epitaxial layer forming a movable mass (40) which is surrounded at the sides by a fixed mass (41); said movable mass (40) being separated from said substrate (1) by an air gap (38) and at the sides from said fixed mass (41) through trenches (33a, 33b, 33c), said movable mass (40) being supported by said fixed mass (41) through anchorage portions (42), characterized in that it comprises a weighting region (26c) comprising tungsten at said movable mass (40).

11. A sensor according to Claim 10, characterized in that said weighting region (26c) extends above said movable mass (40).

12. A sensor according to Claim 11, characterized in that said weighting region (26c) is surrounded by a protective layer (31) of silicon carbide.

13. A sensor according to Claim 11, characterized in that it comprises electronic components (23) formed in a single-crystal epitaxial region (13") in said epitaxial layer (13) and in that said electronic components comprise tungsten contact electrodes (26a).

14. A sensor according to Claim 13, characterized in that adhesive titanium nitride regions (25) extend underneath said weighting region (26c) and said contact electrodes (26a).

15. A sensor according to one of Claims 10-14, characterized in that said substrate (1) has a first conductivity type; and in that it comprises buried conductive regions (2) of a second conductivity type extending in said substrate and selectively facing said epitaxial layer (13); electrically insulating material regions (9a-9d) extending on said buried conductive regions (2) and delimiting therebetween portions of selective contact between said buried conductive regions (2) and said movable (40) and fixed (41) mass; and deep contact regions (18) extending from a surface (16) of said epitaxial layer (13) as far as said buried conductive regions to form deep contacts.

16. A sensor according to one of Claims 10-15, characterized in that said movable mass (40) has movable electrodes (34) facing and interleaved with fixed electrodes (35) extending from said fixed mass (40) to form a sensor of capacitive type; said movable electrodes comprising respective tungsten weighting regions (26c).

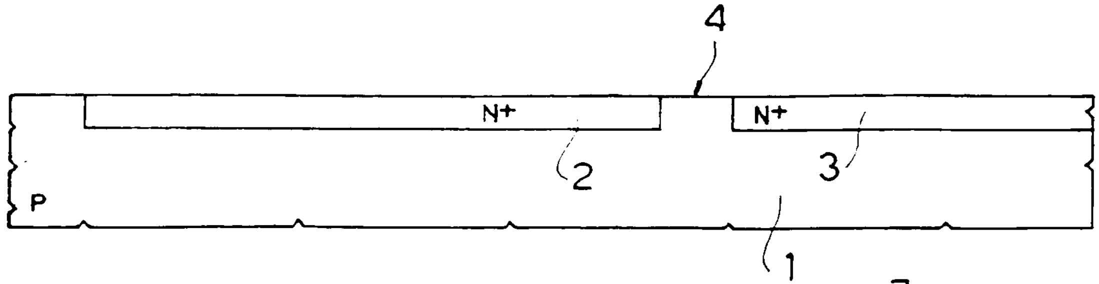

Fig.1

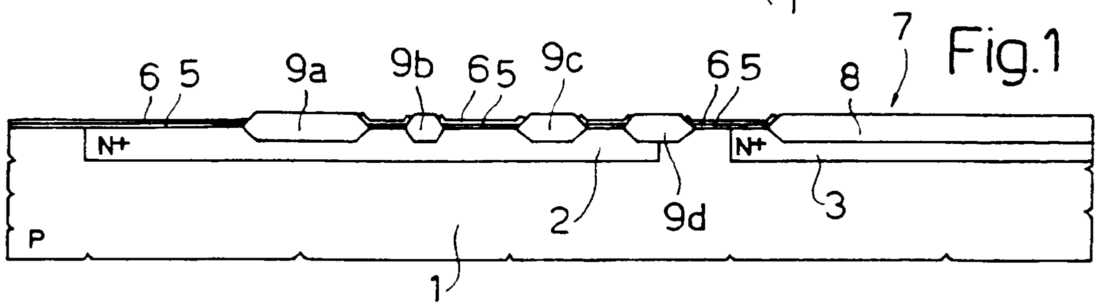

Fig.2

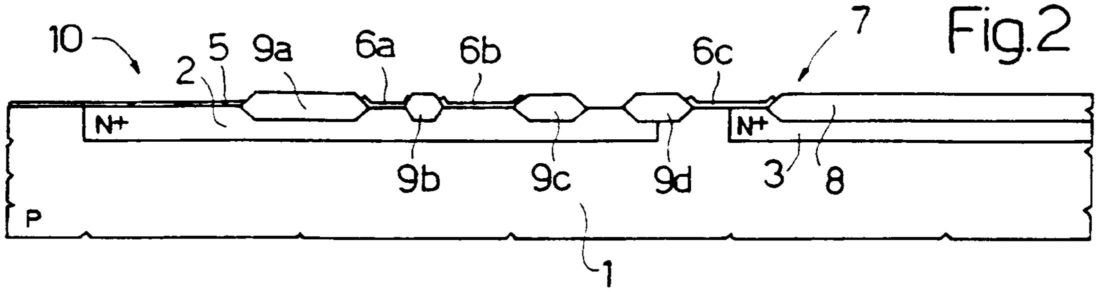

Fig.3

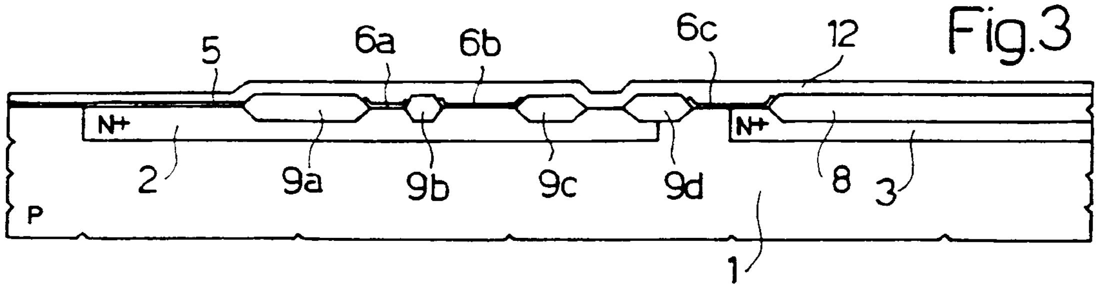

Fig.4

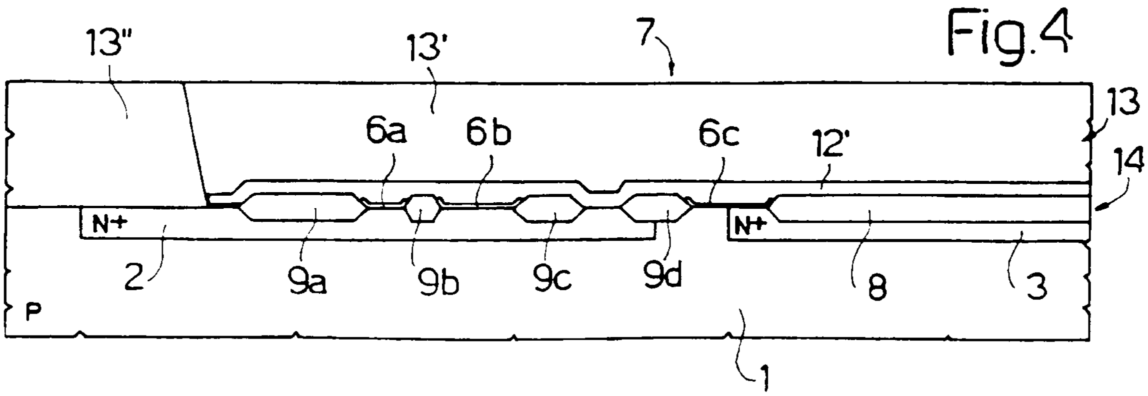

Fig.5

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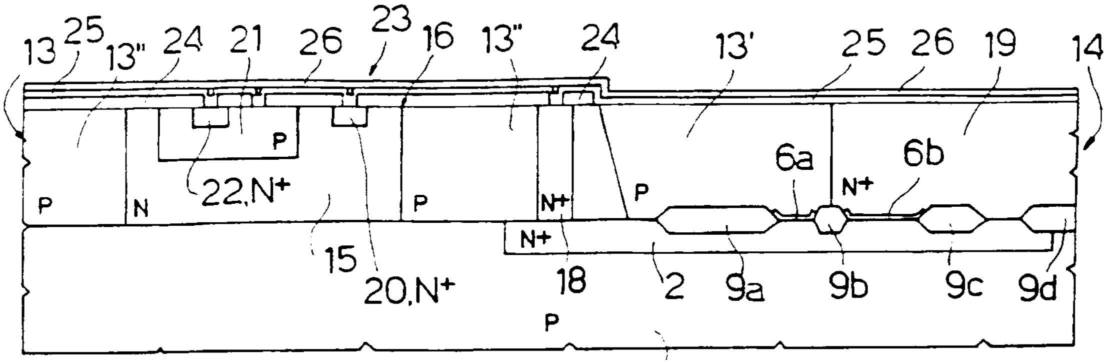

Fig.6

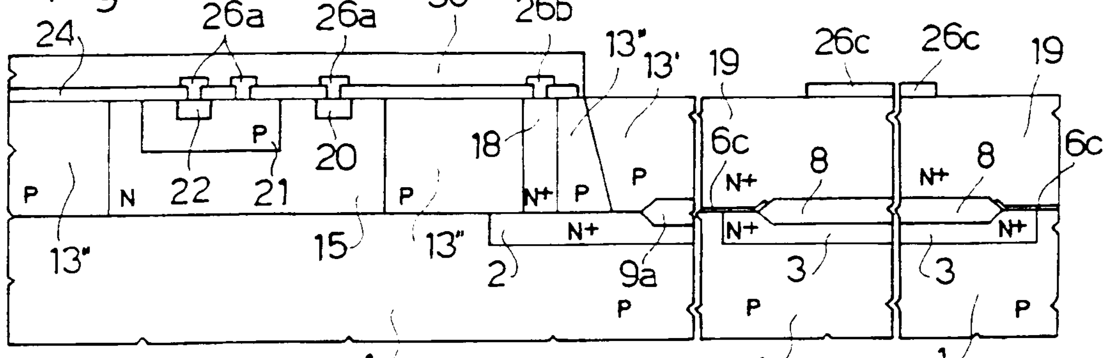

Fig.7

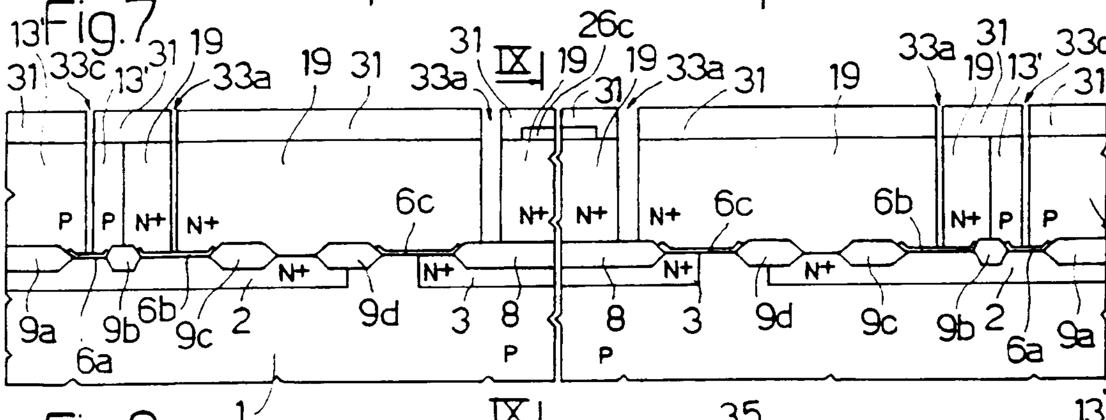

Fig.8

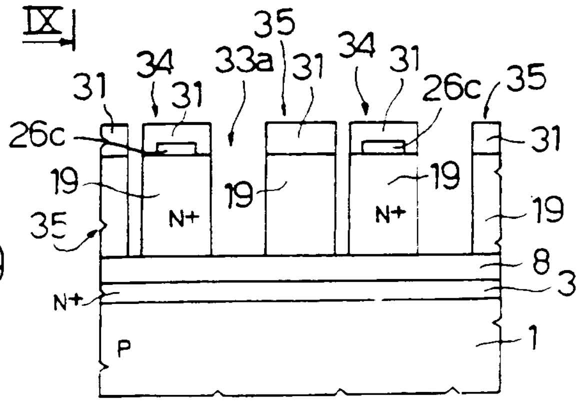

Fig.9

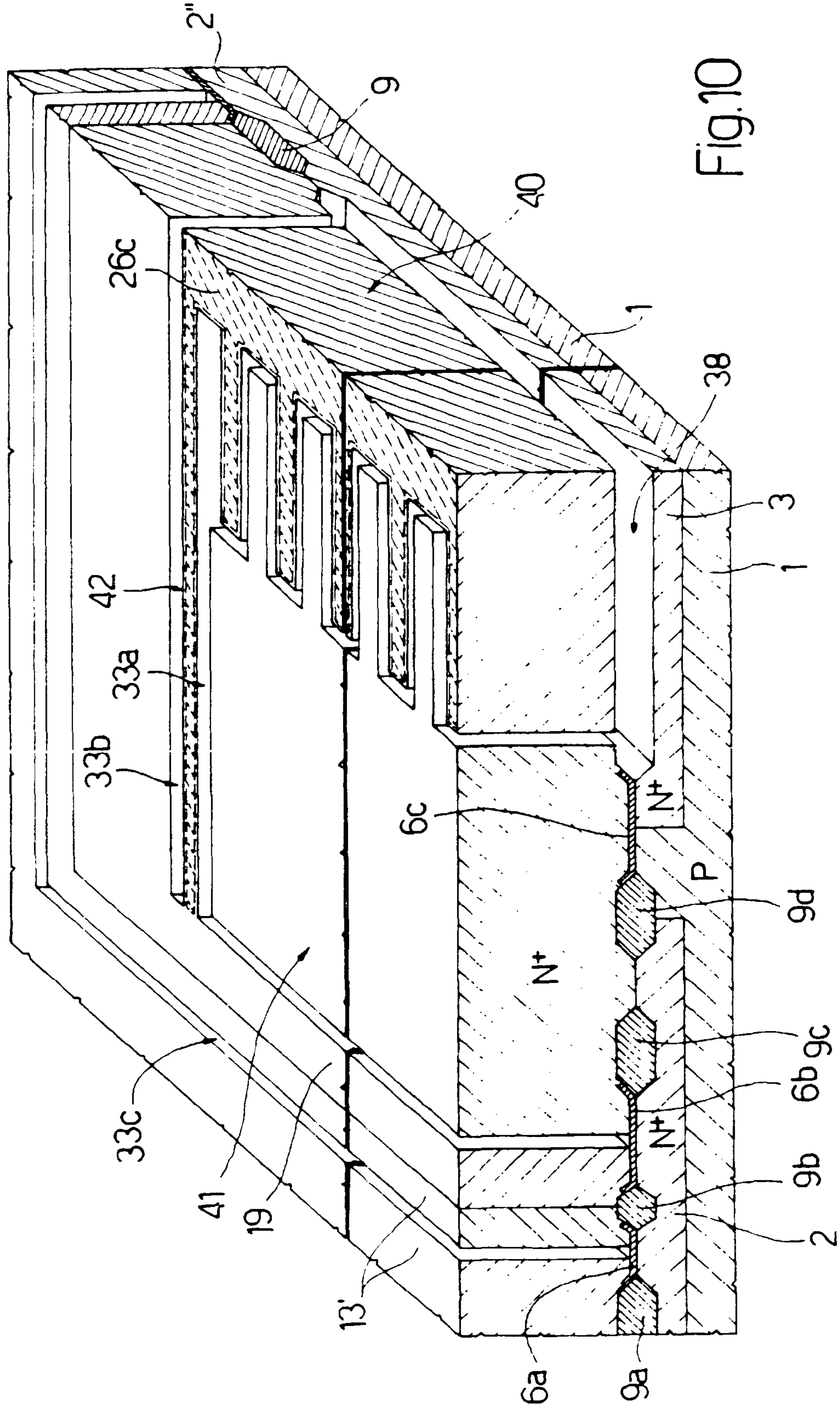

Fig.10

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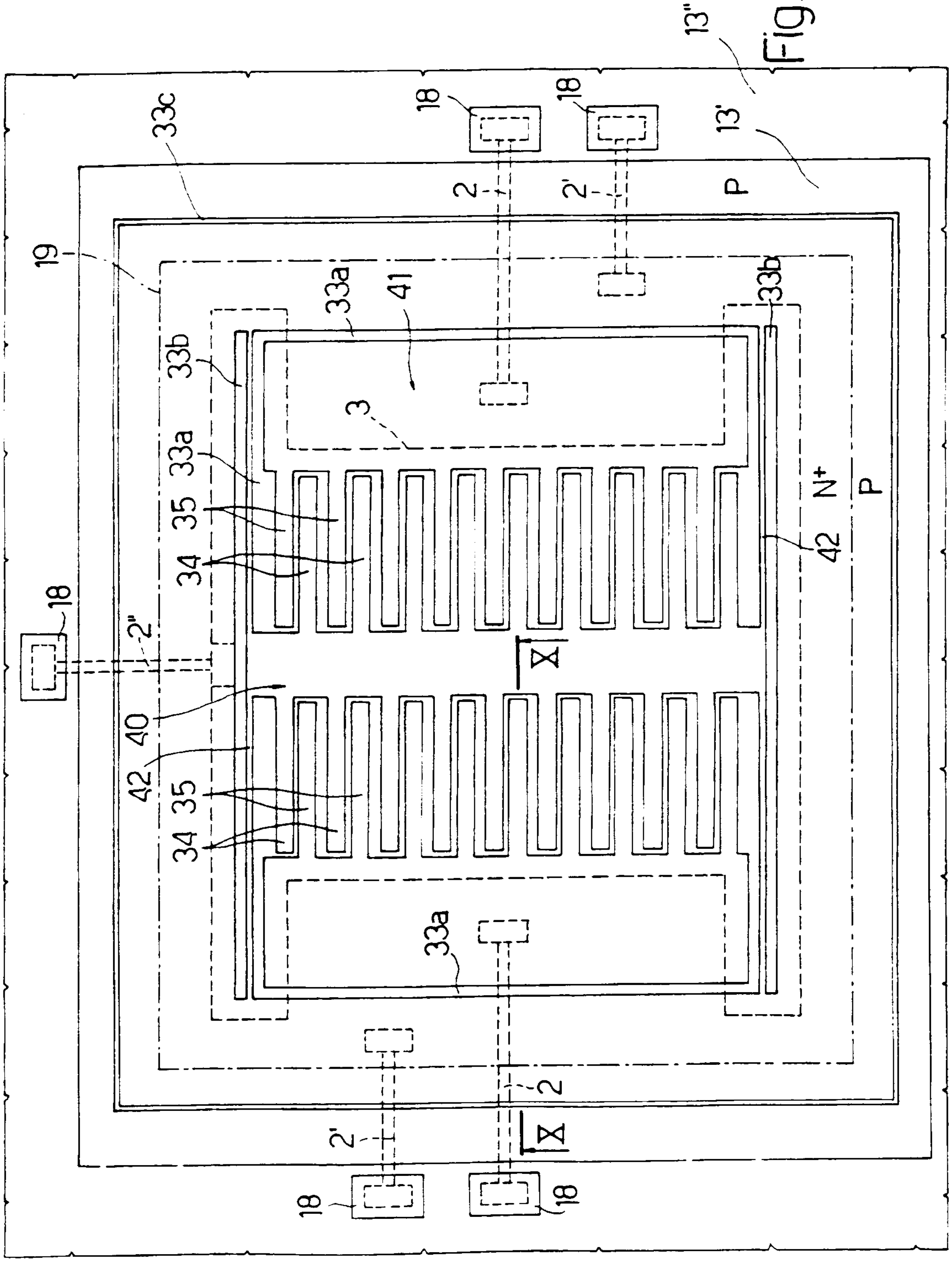

Fig.11

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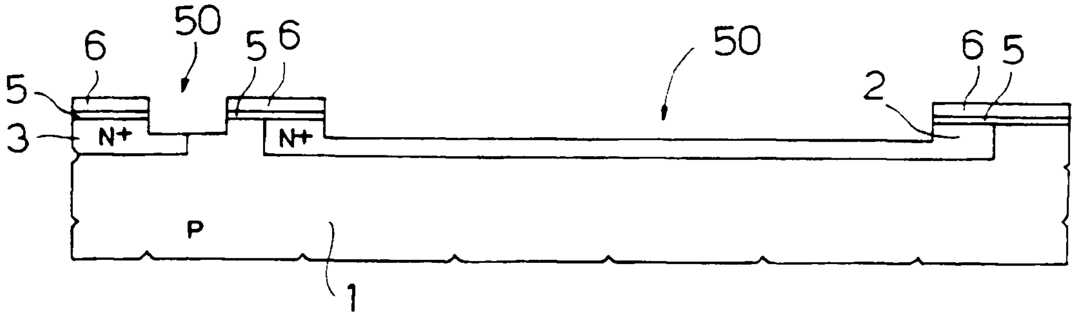

Fig.12

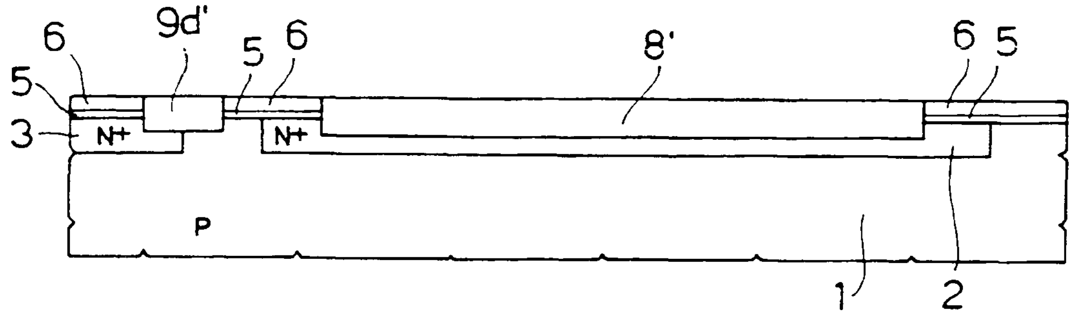

Fig.13

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European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 97 83 0407

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	DE 43 18 466 A (BOSCH GMBH ROBERT) * column 3 - column 4; figures 1-5 * ---	1,4-6,8,10	G01P15/08 G01P15/125
A	US 4 699 006 A (BOXENHORN BURTON) * claims 1,2; figures 1-3 * ---	1,10	
A	US 5 591 910 A (LIN TSEN-HWANG) * claims 1-3; figures 5,6 * -----	1,10	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

G01P

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	26 March 1998	Hammel, E

CATEGORY OF CITED DOCUMENTS

X particularly relevant if taken alone
Y particularly relevant if combined with another document of the same category
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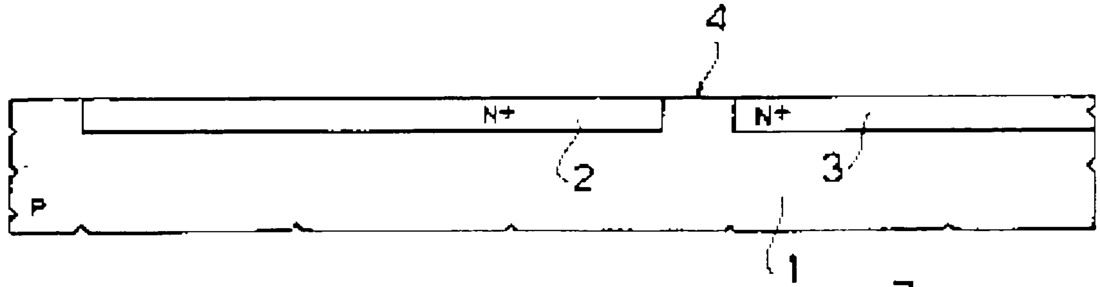

Fig.1

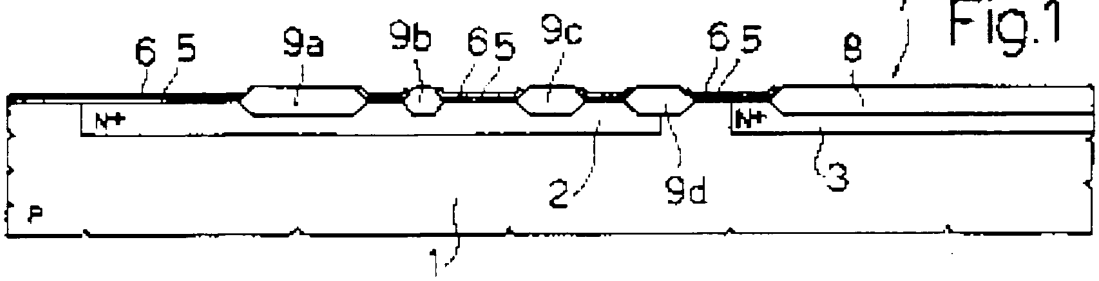

Fig.2

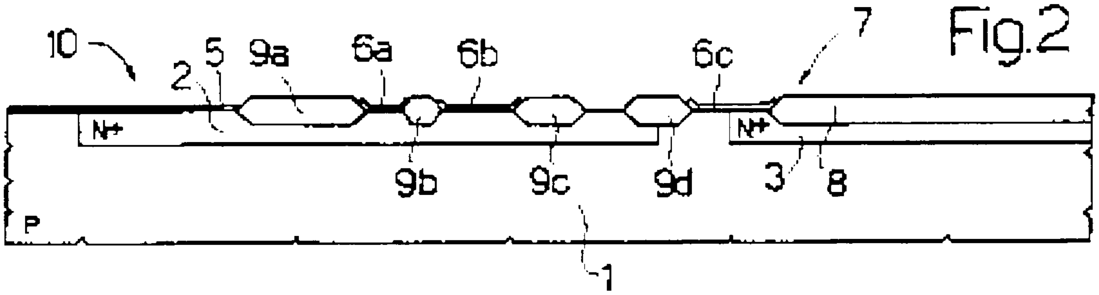

Fig.3

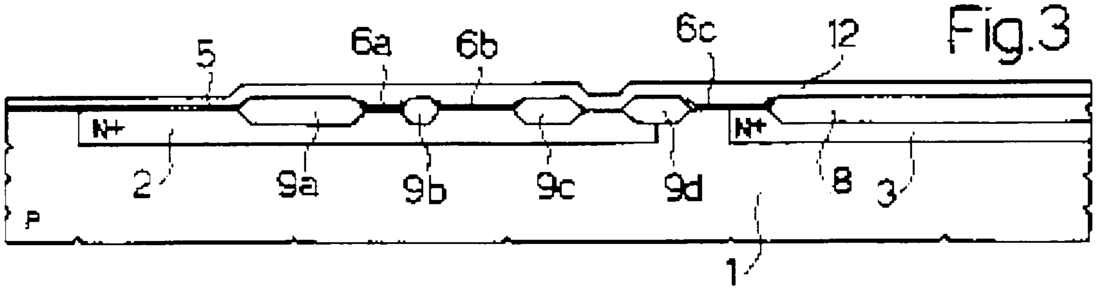

Fig.4

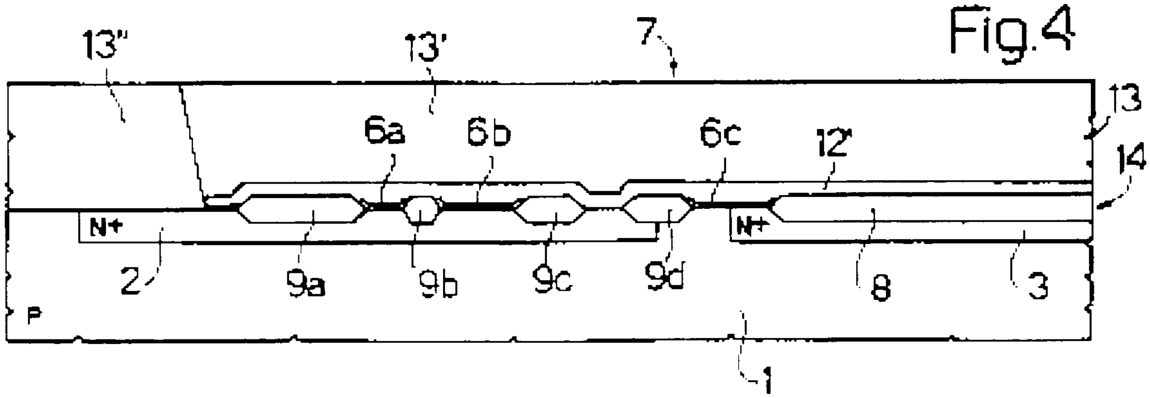

Fig.5

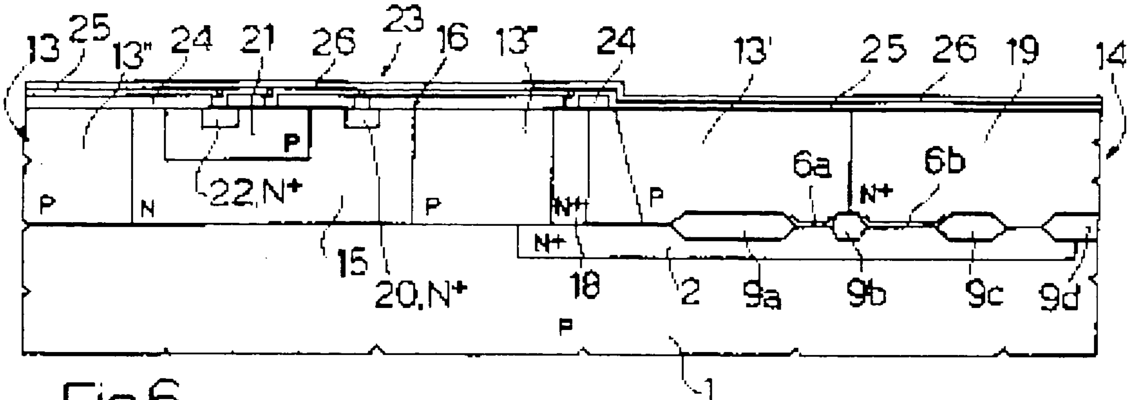

Fig.6

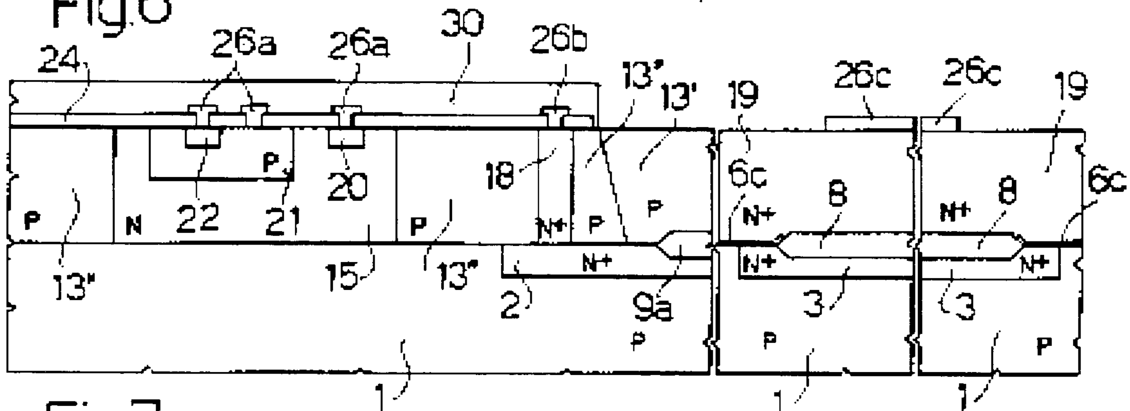

Fig.7

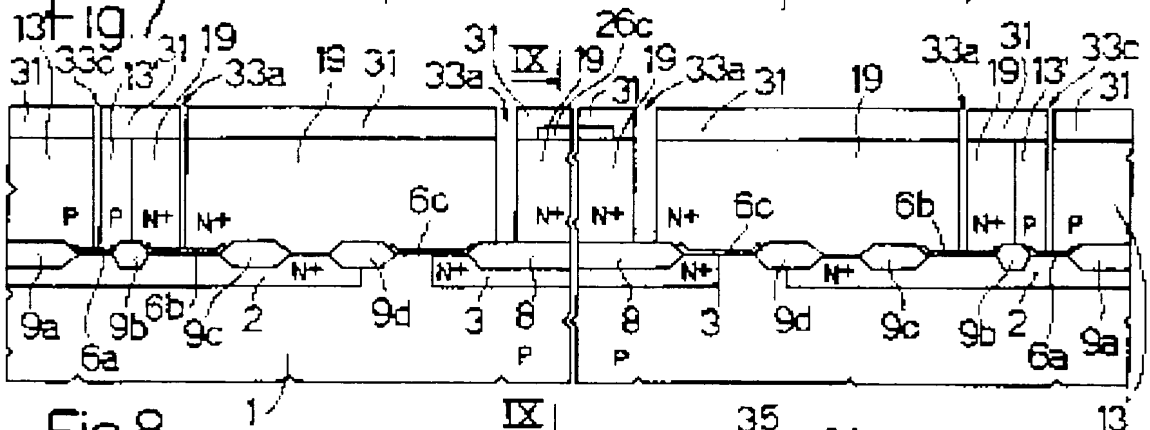

Fig.8

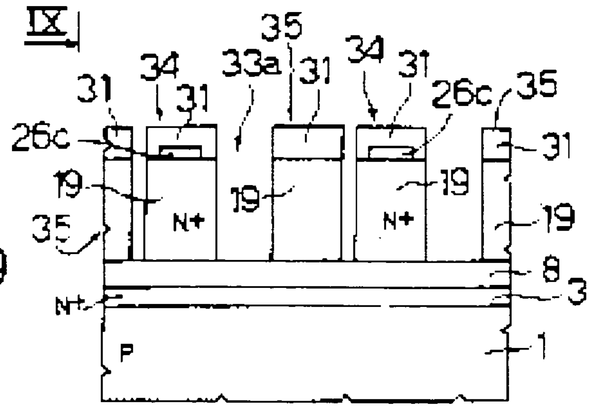

Fig.9

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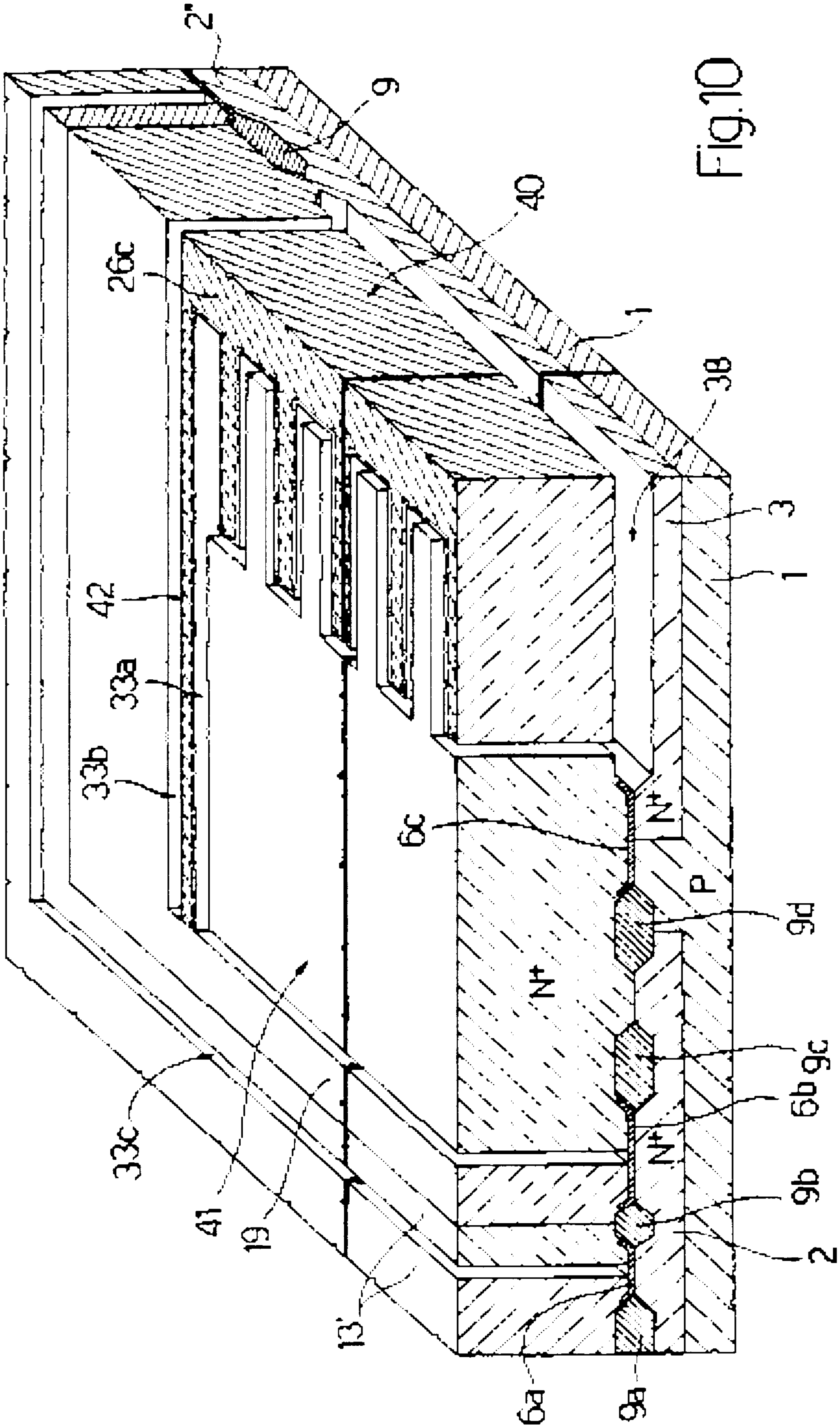

Fig.10

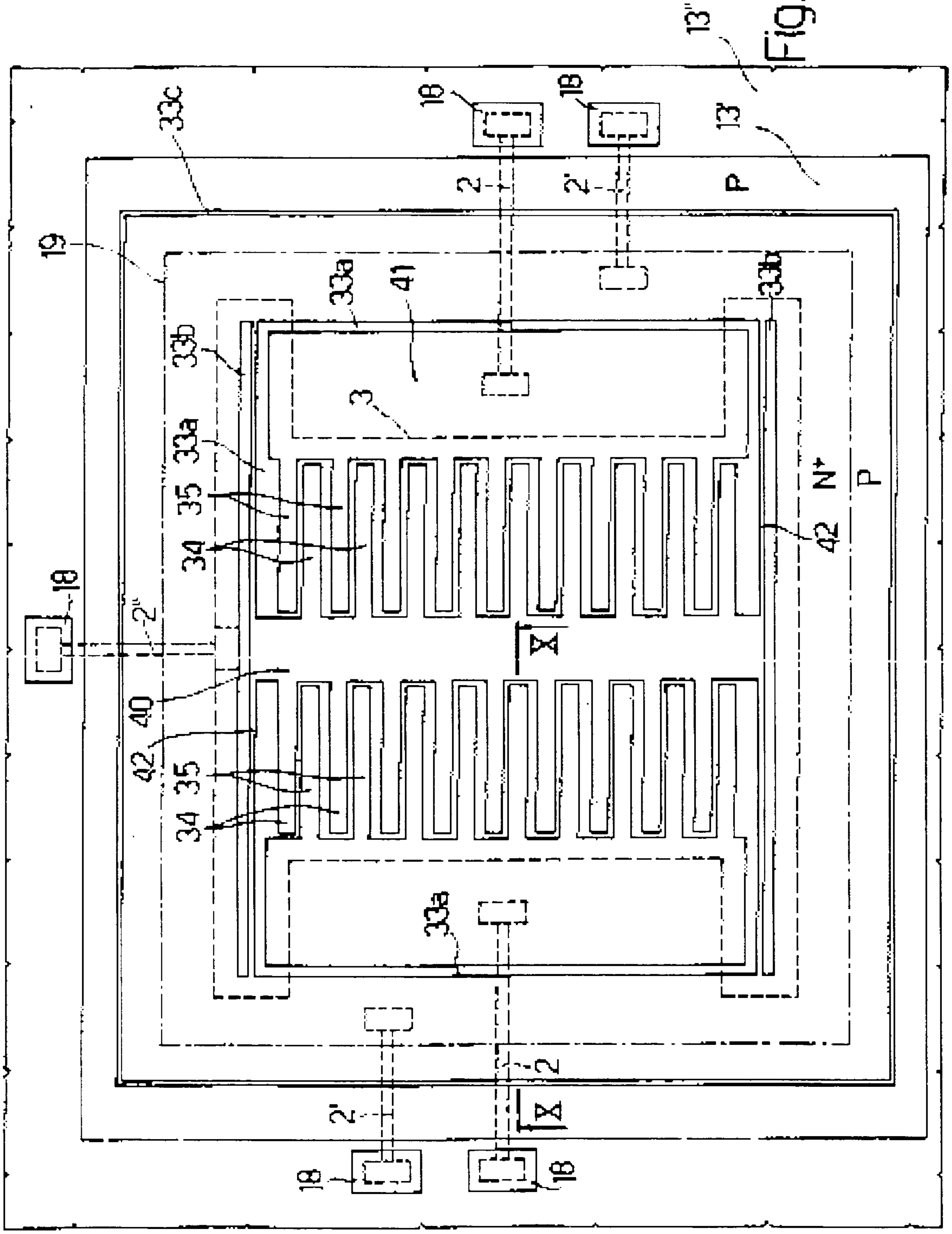

Fig.11

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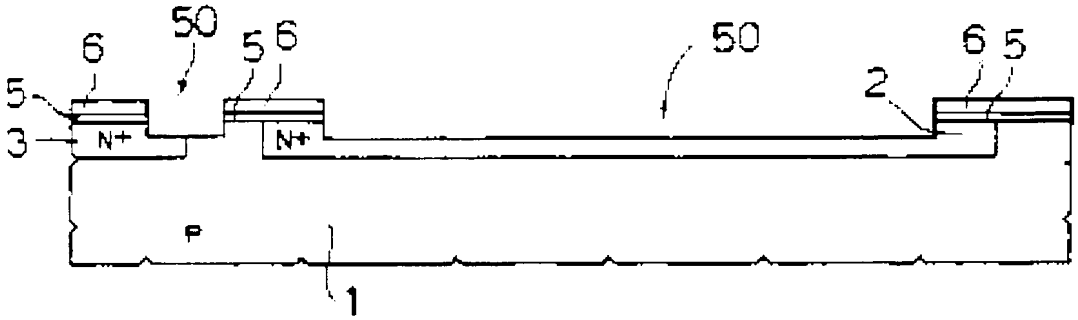

Fig. 12

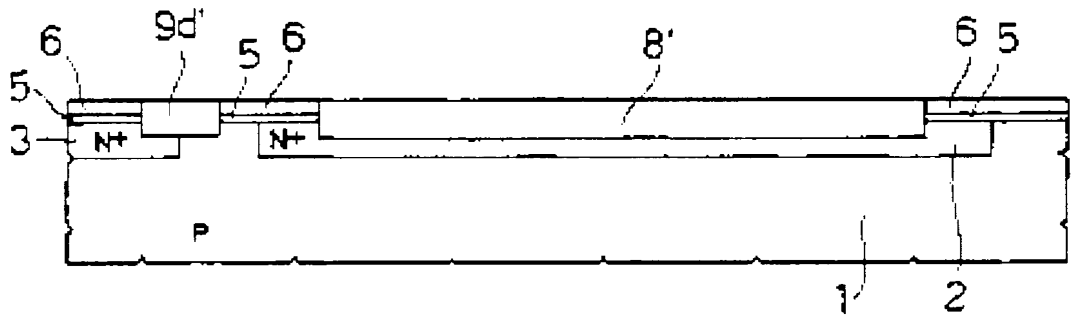

Fig. 13